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A DIRECT MEASUREMENT OF THE CHARGE STATES OF ENERGETIC IRON

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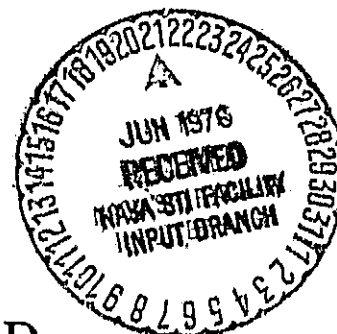
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EMITTED BY THE SUN

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ABSTRACT

The charge states of energetic iron have been measured directly for the first time in a solar particle event of 1974, May 14-15. We find that in the energy interval 0.01 to 0.25 MeV per nucleon, iron is not fully stripped but has a mean ionization state of 11.6. This value is remarkably similar to the mean ionization state of iron in the quiet solar wind and suggests that the charge states were "frozen-in" at a coronal temperature of $\sim 1.5 \times 10^6$ °K.

Subject headings: energetic solar particles - composition and
energy spectra

I. INTRODUCTION

Among the more characteristic features of the composition of energetic solar particles below about 10 MeV per nucleon is the systematic enrichment or overabundance of heavy elements (Price et al. 1971; Fleischer and Hart 1973; Mogro-Compero and Simpson 1972; Hovestadt et al. 1973) which in many cases increases with decreasing particle velocity (Price et al. 1971; Lanzerotti, MacLennan, and Graedel 1972; Hovestadt et al. 1973; Crawford et al. 1975; O'Gallagher et al. 1976). The relative abundances, on the other hand, have been found to vary not only from one solar event to the next, but also during a given event (Armstrong and Krimigis 1975; Armstrong et al. 1976; Van Allen, Venkatarangan, and Venkatesan 1974). In many models it is assumed that low energy solar particles are not fully ionized, and the observations are explained by some combination of charge to mass dependent acceleration, escape and propagation (Cartwright and Mogro-Compero 1972; Ramudarai 1973; Price et al. 1971; see also Hovestadt (1974) and Gloeckler (1975) for recent reviews of observations and models). Direct measurements of the charge states of heavy ions are therefore clearly important. In this Letter we present the first direct measurement of the ionization states of energetic iron in a solar flare particle event. Previously, we reported that carbon and oxygen below ~ 1 MeV per nucleon are nearly fully stripped (Gloeckler, Fan, and Hovestadt 1973; Gloeckler et al. 1975a) and that the mean charge states of C and O observed in nine solar flare particle events are 5.7 and 6.2 respectively (Sciambi 1975; Sciambi et al. 1976).

II. INSTRUMENTATION

The measurements reported here were made using the ULET sensor and the Electrostatic Energy vs. Charge Analyzer (EECA) of the University of Maryland/Max-Planck-Institut experiment on the earth orbiting satellite

IMP 8. ULET is a dE/dx vs. E counter telescope which measures the atomic number and energy of an incoming particle (Hovestadt and Vollmer 1971). Because the ΔE element is a very thin ($\sim 150 \mu\text{g}/\text{cm}^2$) flow-through proportional counter the low energy thresholds for identifying carbon, oxygen and iron using 2 parameter measurements are about 100 keV per nucleon. The EECA sensor (Tums et al. 1974), on the other hand, measures directly the ionization state and kinetic energy of an incoming ion. After deflection in a known electrostatic field, the energy and amount of deflection determine the charge state of the incoming particle. The energy range of EECA of ~ 35 to 1200 keV per charge is divided into seven discrete energy per charge intervals fixed by the locations and widths of 7 rectangular solid state detectors. The energy signal from each detector is pulse-height-analyzed.

III. OBSERVATIONS

During the ten day period, 1974 May 7-17, heavy elements in the composition of a solar particle event were unusually overabundant, with the event-averaged iron as abundant as oxygen at 1 MeV per nucleon (Gloeckler et al. 1975b; Hovestadt et al. 1975). In Figure 1 we show the coincidence counting rates for $Z \geq 1$ nuclei (predominantly low energy protons and alphas) and for $Z > 2$ nuclei respectively as well as the ratio, R , of light to heavy nuclei. The persistent enhancement of heavy nuclei is evident from this ratio which drops from its usual value of ≤ 200 to about 20 on May 7 and remains at this low value for 10 days. We measured the charge states of iron during the intensity increase of May 14-15 which was presumably the result of a west limb 2N flare at 2120 on May 13.

IV. RESULTS

In Figure 2 we show the charge histograms for ions between 130 to 210 keV per charge derived from pulse-height analysis of detector P3 energy signals which were accumulated for a one day period of 1974 May 14 7^h to May 15 5^h. Since the energy per charge window for each of the seven rectangular detectors is fixed by its location and width as well as by the geometry of the collimator-deflection system, pulse-height analysis of the energy signal may be directly related to the charge state Q of the incoming ion. In these histograms the dominant peak (at ~ 170 keV) corresponds to $Q = 1$ particles, the middle peak (at ~ 340 keV) to $Q = 2$ ions and the smallest peak (at ~ 1 MeV) to ions with charge states in the 5 to 14 range. In particular, note the absence of $Q = 3$ and 4 and > 14 charge states.

Except for protons and helium, which are associated with $Q = 1$ and $Q = 2$ charge states respectively, the EECA sensor does not provide information on the atomic number of the particle. It is necessary, therefore, to know the relative abundance of the dominant heavy elements C, O and Fe before one can establish the extent of ionization of iron.

From the pulse-height analysis data of the ULET we have determined the relative abundances for He, C, O and Fe for the May 14-15 solar particle event to be approximately 17:0.5:1:1 as shown in Table 1. Using these observed abundances we can then calculate the expected pulse-height distribution for a given detector under different assumptions regarding the iron charge states and compare this distribution to the observed charge histogram. The dashed curve in Figure 2(a) gives the calculated response assuming that the charge states of iron lie between 9 and 14. The dashed curve in Figure 2(b) shows the response assuming iron is fully stripped. We can

conclude from the excellent fit to the observed histogram in Figure 2(a) that iron in the iron rich event of 1974, May 14-15 is not fully stripped.

In Figure 3 we show the event-averaged energy spectra for helium, carbon, oxygen and iron derived from the ULET pulse height data at the higher energies as well as the helium and iron spectra calculated from the charge histogram of the various detectors of the EECA sensor at the lower energies. In the EECA data we have assumed all charge state 2 particles to be helium and have taken as the iron spectrum the calculated $Z \geq 6$ intensities (corresponding to $Q \geq 5$ peaks in the charge histograms) reduced by a factor of 2.5. We note the following features of these energy spectra.

- (1) There is good agreement in the absolute intensities for helium and iron derived from the ULET (solid symbols) and EECA (open symbols) data respectively in the common energy intervals. (0.25 to 0.6 MeV per nucleon).
- (2) There is no significant bendover in the spectra down to the lowest observable energies (10 keV per nucleon for iron and 40 keV per nucleon for helium).
- (3) There is no pronounced energy dependence in the heavy ion enhancement.
- (4) The O/C ratio is anomalously high (~ 7) in the energy interval of ~ 1 to 4 MeV per nucleon (see Table 1), reminiscent of the ratio in the anomalous component of the quiet-time cosmic rays (McDonald et al. 1974; Klecker et al. 1975, 1976; Gloeckler 1975).

V. IONIZATION STATES OF IRON

To determine the distribution of the ionization states of iron we assume that the peak corresponding to charge states 5 to 14 in each of the charge histograms is produced primarily by the elements C, O and Fe. Furthermore, we take the distribution of ionization states of carbon and oxygen in the

May 14-15 event to be the same as in the nine solar particle events studied by Sciambi et al. (1976) who found the mean charge states to be remarkably invariant from event to event with an average distribution as given in column 2 of Table 2. We can then subtract from the charge histograms the contribution of C and O, whose relative abundances at slightly higher energies are given in Table 1. The ionization states of iron are obtained by varying systematically the relative abundances of each charge state in the range 9 to 14 until the best χ^2 fit to the charge histogram is obtained. The results are shown in column 3 of Table 2. The most abundant charge states of iron are 11 and 12 and mean ionization state is 11.6.

The charge state distributions of iron measured in the 1974 May 14-15 event as well as those of oxygen in nine other solar particle events are quite similar to those found in the quiet solar wind (see column 4 of Table 2). On the other hand, the Fe/O ratio in the solar wind is ~ 0.17 which is considerably different from our value of ~ 1 found in this "iron rich" event.

V. DISCUSSION

Our results that energetic iron below 0.28 MeV per nucleon in the May 14-15 "iron rich" particle event is only partially ionized is consistent with the conclusions of O'Gallagher et al. (1976) that the mean charge states of iron in the energy range 0.5 to 5 MeV per nucleon in an ordinary solar particle event (1974 September 19) is 10 ± 5 . On the other hand Sullivan and Price (1973) argue that ~ 2 MeV per nucleon iron in the solar flare event of 1974 January 25 is fully stripped. It is not clear at this point whether this discrepancy is due to the difference in the energies of these two measurements or indicates a variability in the degree of ionization of iron between flares.

When we compare the charge states of energetic ions (columns 2 and 3 of Table 2) with those found in the quiet solar wind (column 4) and calculated charge states in the solar corona of temperature 1.5×10^6 °K (column 5) the overall agreement and consistency stands out. The simplest conclusion based on these comparisons is that the source of heavy ions observed in this solar particle event is in the lower solar corona where the temperature is between $1-2 \times 10^6$ °K, and that the charge states are not changed in subsequent storage and/or propagation to earth.

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TABLE 1

Event-Averaged Abundances of He, C and Fe Relative to Oxygen
for the 1974 May 14-15 Solar Particle Event

Chemical Element	Energy Interval (MeV per nucleon)			
	0.15-0.3	0.3-0.6	0.6-1.0	1.0-4.0
He		1730 ± 225	1620 ± 350	800 ± 350
C	43 ± 11	55 ± 13	32 ± 14	15 ± 9
O	$\equiv 100$	$\equiv 100$	100	100
Fe	90 ± 16	127 ± 32	108 ± 33	75 ± 31

TABLE 2

Ionization State Abundances of Carbon, Oxygen and Iron

Charge State	Average of Nine Solar Particle Events ^(a) 15 to 600 keV/nuc	1974 May 14-15 Solar Particle Event 8 to 250 keV/nuc	Solar Wind ^(b)	Solar Corona ^(c)
C ⁺⁵ /C	0.25 ± 0.04			0.19
C ⁺⁶ /C	0.75 ± 0.05			0.81
O ⁺⁶ /O	0.72 ± 0.05		0.77	0.76
O ⁺⁷ /O	0.23 ± 0.05		≤ 0.15	0.23
O ⁺⁸ /O	0.05 ± 0.04			0.01
Fe ⁺¹⁰ /Fe		0.14 ± 0.04	0.24	0.14
Fe ⁺¹¹ /Fe		0.31 ± 0.06	0.21	0.26
Fe ⁺¹² /Fe		0.35 ± 0.07	0.14	0.32
Fe ⁺¹³ /Fe		0.20 ± 0.05		0.16

(a) Sciambi et al. (1976)

(b) Bame et al. (1972)

(c) Calculated at $T_e = 1.58 \times 10^6$ °K using model of Jordan (1969).

FIGURE CAPTIONS

Fig. 1--(a) Counting rates of $Z \geq 1$ particles (primarily 0.43 - 1.5 MeV protons and 0.25 to 7.0 MeV per nucleon alpha particles) and $Z > 2$ particles for the 1974 May 5 to 20 time period. (b) The time dependence of the ratio of $Z \geq 1$ to $Z > 2$ particles. Note that the ratio of light to heavy ions is small and relatively constant from May 7 to 16 despite large intensity variations in the individual counting rates. SEV is the angle between the earth-sun and the earth-satellite vectors.

Results presented in this Letter have been obtained from data recorded during the one day period of 1974 May 14 7^h to 15 5^h.

Fig. 2--Charge histograms of the background-corrected pulse height data for the P3 detector of EECA. The dashed curves represent the calculated detector response under two different assumptions: (a) The charge states of iron are between 9 and 13 and distributed as given in column 3 of Table 2, (b) the charge states of iron are all 26. On the basis of comparison between the calculated and measured charge histogram we conclude that iron in this solar particle event is not ionized beyond charge 14.

Fig. 3--Differential energy spectra for He, C, O and Fe. Obtained from the EECA sensor (open symbols) and the ULET sensor (solid symbols) of the University of Maryland/Max-Planck-Institut IMP 8 experiment.

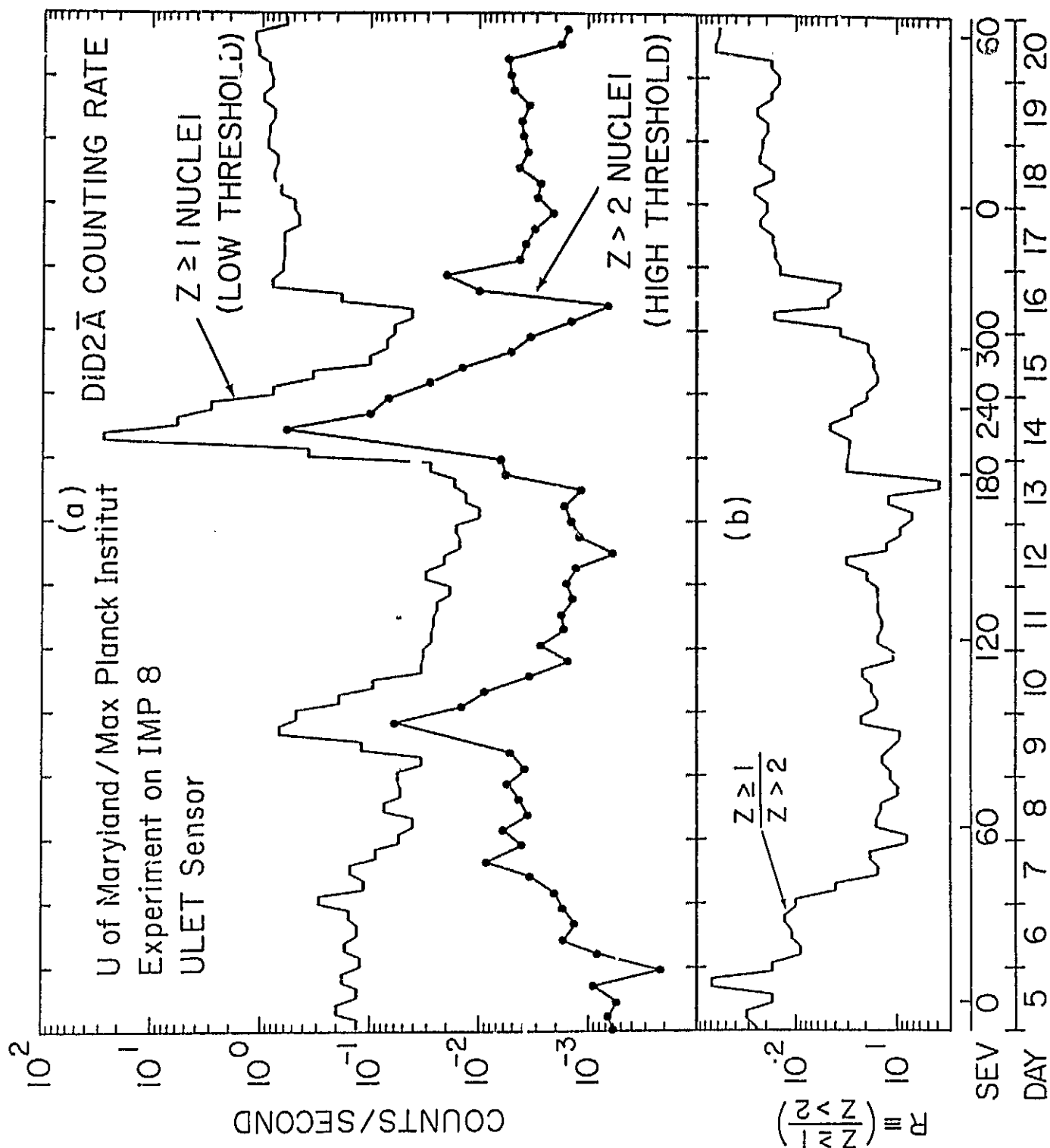


FIGURE 1

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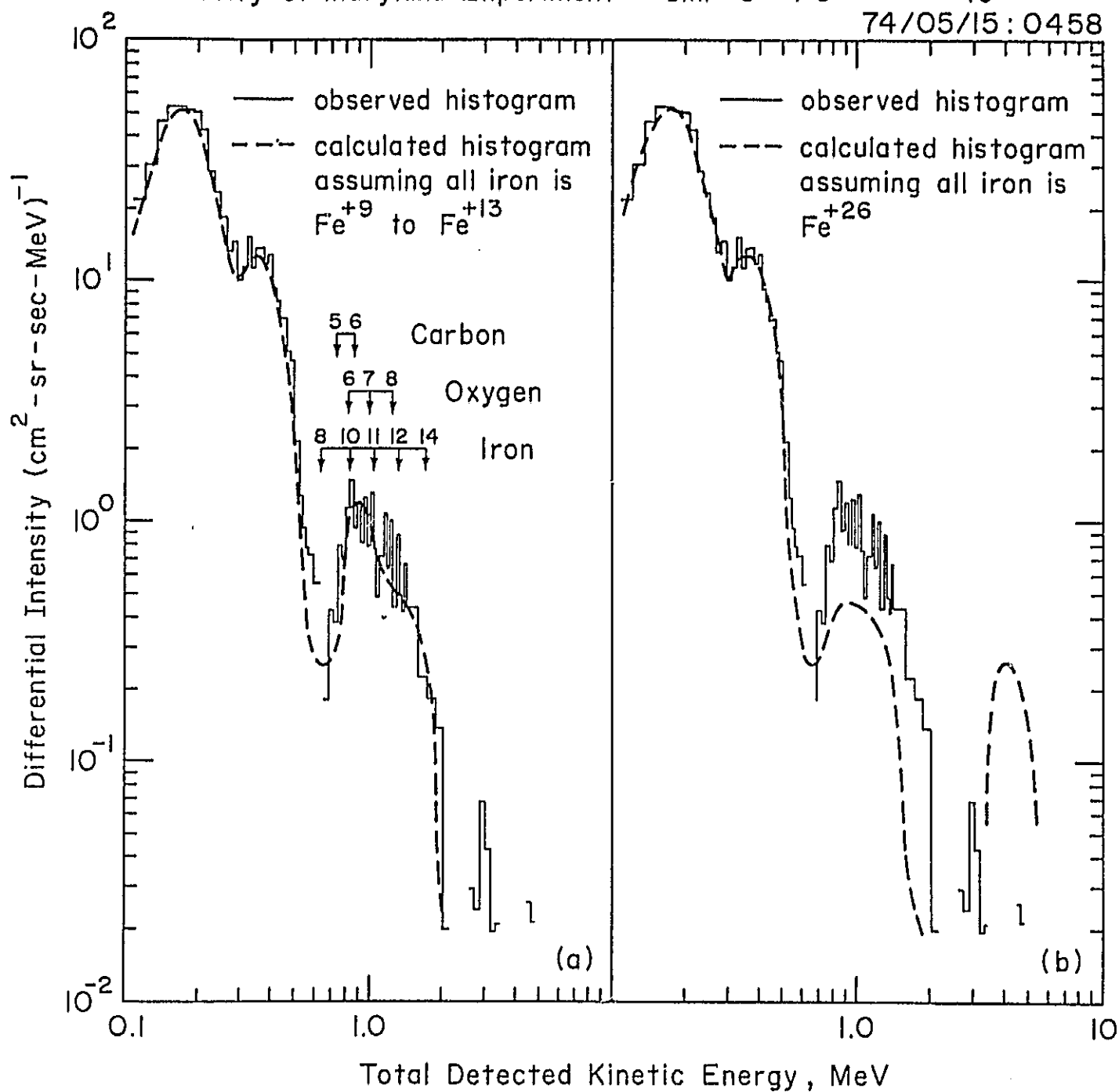


FIGURE 2

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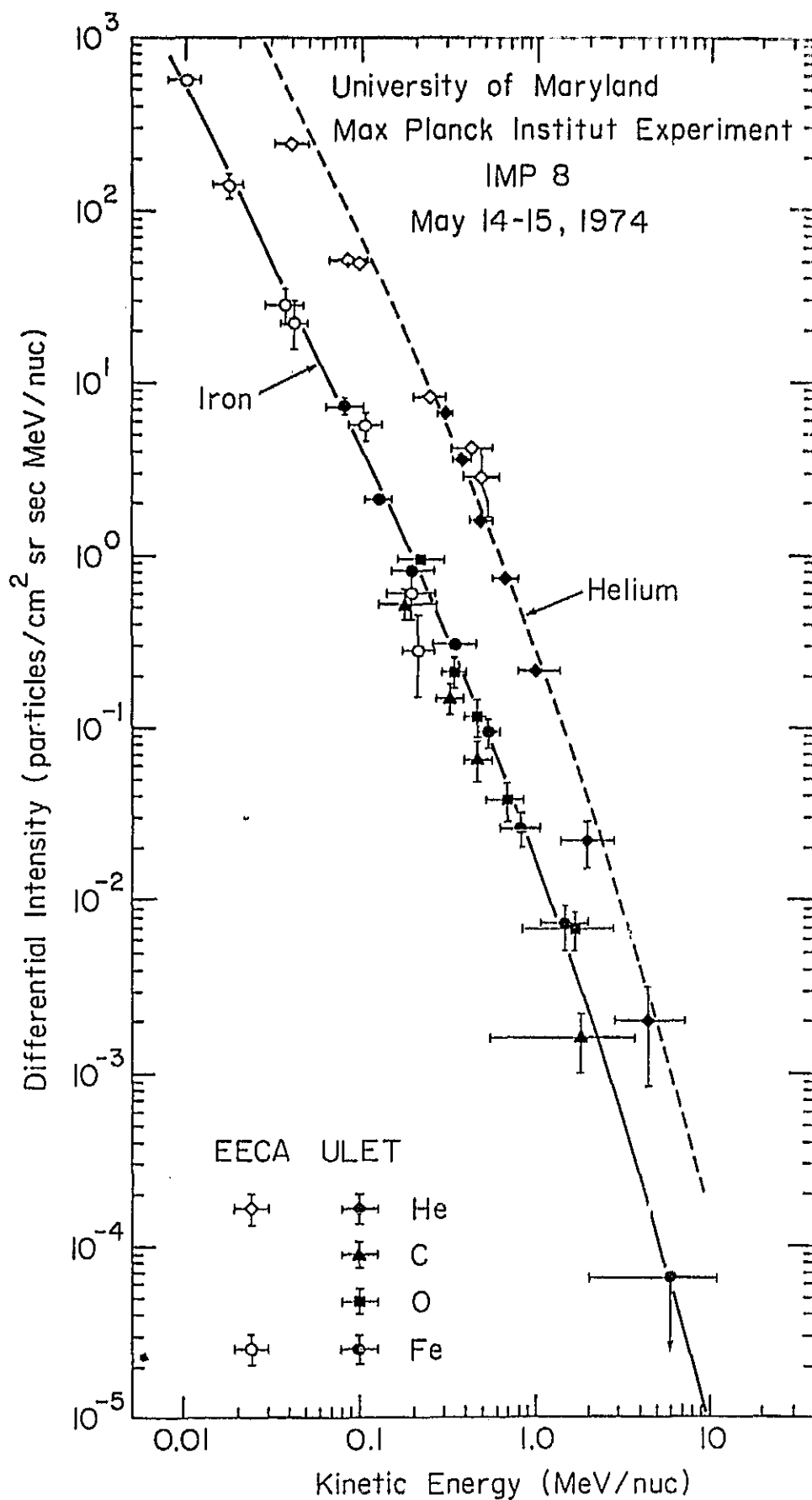


FIGURE 3

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